Semi-annual Report for July - December, 1995
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NASS-31716

Abstract

The algorithm-development activities at USF during the second half of 1995 have concentrated on field data collection and theoretical modeling. Two bio-optics experiments were conducted, one in the Dry Tortugas and Loop Current area, and one in the Arabian Sea. The data from these cruises are currently being reduced.

Tasks Accomplished:

1. R/V Bellow and R/V Suncoaster cruises were conducted jointly near the Dry Tortugas between August 21 and August 28, 1995. Tasks included bottom, and coral albedo measurements by divers, remotely operated vehicle (ROV) and autonomous underwater vehicle (AUV) measurements of optical properties, partitioning of the absorption coefficients of water samples, taking conductivity-temperature-depth (CDT) and chlorophyll fluorescence profiles, and collecting surface remote sensing reflectance data. Accompanying the cruise were two P3 aircraft overflights with CASI, PHILLS, and DAEDALUS sensors onboard.

2. Remote sensing reflectance and absorption coefficients of partitioned surface water samples were collected on a cruise in the Arabian Sea onboard the R/V Thomas Thompson between June 21 and July 13. In addition to ship activities, our group provided instrumentation and personnel to intercalibrate with P3 aircraft instruments. The P3 aircraft over-flown the ship tracks with the Airborne Oceanographic Lidar sensor.

3. A paper titled "Optical Model of Ocean Remote Sensing: Application to Ocean Color Algorithm Development" by Carder et al. was presented in Committee on Space Research (COSPAR) Colloquium: Space Remote Sensing of Subtropical Oceans(SRSSO) in Taipei, Taiwan on September 12-16, 1995.

The Coastal Zone Color Scanner spectral-ratio algorithm for chlorophyll-like pigments was reasonably accurate as long as the important back-scattering and absorbing constituents in the water covaried with chlorophyll. When this covariance disappeared, such as for regions with terrigenous inputs of gelbstoff and suspended sediments or for shallow waters, the accuracy decreased. Similarly, when the absorption per unit chlorophyll *a* changed unpredictably due to the pigment package effect (e.g., for high-latitude waters), derived pigment could be less than half the measured values.

SeaWiFS, OCTS, and MODIS all have additional channels that can help in separating the effects of gelbstoff, pigment packaging, absorbing aerosols, and bottom reflection. To develop algorithms to deal with these effects, an optical model is applied to develop algorithms for 1) the absorption coefficient for phytoplankton, $a_\phi(\lambda)$, 2) the absorption coefficient for gelbstoff, $a_g(\lambda)$, 3) the back-scattering coefficient for tropical, subtropical, and summer temperate waters (non-upwelling), $b_b(\lambda)$, 4) the chlorophyll *a* concentration [*chl a*] for subtropical and summer temperate waters, 5) the chlorophyll *a* concentration for upwelling and high-latitude waters, and 6) a strategy for determining the regimes in 4) and 5).

Examples of the performance of the algorithms were shown as well as the perturbations that bottom depth and albedo have on remote-sensing-reflectance spectra measured with an airborne imaging spectrometer for the Florida Keys. For non-perturbed subtropical waters, rms accuracies for [*chl a*], $a_\phi (\lambda)$, and $a_{g(}\lambda)$ were 30%, 30%, and 43%, respectively.

4. A paper titled "An Bathymetric Algorithm of Water-leaving Radiances in AVIRIS Imagery: Use of A Reflectance Model " by Chen et al. was presented in Committee on Space Research (COSPAR) Colloquium: Space Remote Sensing of Subtropical Oceans(SRSSO) in Taipei, Taiwan on September 12-16, 1995.

AVIRIS (Airborne Visible-Infrared Imaging Spectrometer) is a test bed for future high-resolution spacecraft imaging spectrometers. AVIRIS has 10 nm spectral and 20 m spatial resolutions. It has 224 channels from 400 to 2400 nm, and it now has a nearly comparable signal-to-noise ratio with that of the Coastal Zone Color Scanner (CZCS) with only minor (3x3) pixel binning. For coastal ocean applications much larger signals are typical, compared to those offshore. Thus, adequate signal levels for many nearshore applications can be achieved by binning 25 to 100 pixels together.

In November 17, 1992, AVIRIS data were collected from a NASA ER-2 aircraft flying at 65,000 feet altitude on two NW-SE flight lines. These lines were flown at about 11 A.M. Eastern Standard Time over Card Sound, Florida. The shoreward scenes included complex bathymetric and topographic features that were expected to have effects on the wind and light fields as well as the hydrodynamics.

The AVIRIS preflight calibration was adjusted to be consistent with the in-flight performance of the instrument. Recalibration process was performed on the sensor using the method of Carder et al. (1993). The recalibrated data, representing total radiance at the sensor, was then partitioned into direct and reflected atmospheric path radiance and radiance upwelled from beneath the water surface (water-leaving radiance).

At the time of the overflights, the remote sensing reflectance spectra(R_{rs}) of water patches within view of the spectrometer were taken using a field spectrometer were determined using the methodology described in Carder and Steward (1985). To improve spectral resolution to 6 nm, a 200 micron entrance slit was added to the Spectron Engineering radiometer model 590. A 10% gray, diffuse reflector (Spectralon) a NIST-traceable standard from Labsphere, was used to convert downwelling global irradiance to upwelling radiance for measurement by the Spectron radiometer.

The water-leaving radiance values from AVIRIS derived high R_{rs} values in Card Sound area, south of Biscayne Bay, which suggested that the bottom depth was very shallow or the water was very turbid for the Bay at the time of the study. Using a model developed for hyperspectral remote sensing reflectance , the water depth was derived from AVIRIS data and compared to the *in situ* measurements and bathymetric charts.

5. A paper titled "Estimating primary production at depth from remote sensing" by Lee at el. has been accepted for publication in Applied Optics.

Using a common primary production model, and identical photosynthetic parameters, four different methods were used to calculate quanta (*Q*) and primary production (*P*) at depth for a study of high-latitude, North Atlantic waters. The differences among the 4 methods relate to the use of pigment information in the upper water column. Methods 1 and 2 use pigment biomass (*B*) as an input, and a subtropical, empirical relationship between $K_d(\lambda)$ (diffuse attenuation coefficient) and *B* to estimate *Q* at depth. Method 1 uses measured *B*, but Method 2 uses CZCS-derived *B* (subtropical) as inputs. Methods 3 and 4 use phytoplankton absorption spectra ($a_\phi(\lambda)$) instead of *B* as inputs, with Method 3 using empirically derived $a_\phi(\lambda)$ and $K_d(\lambda)$ values, and Method 4 using analytically derived $a_\phi(\lambda)$ and $a(\lambda)$ (total absorption coefficient) spectra based on hyperspectral remote measurements.

In comparing calculated to measured values of $Q(z)$ and $P(z)$, Method 4 provided the closest results [$P(z)$: $r^2 = 0.95$ (n = 24); and $Q(z)$: $r^2 = 0.92$ (n = 11)]. Method 1 gave the worst results [$P(z)$: $r^2 = 0.56$; and $Q(z)$: $r^2 = 0.81$]. These results indicate that the analytically derived $a_\phi(\lambda)$ and $a(\lambda)$ can be applied to accurately estimate $P(z)$ based on ocean-color remote sensing. Curiously, application to subarctic waters of algorithms for *B* and K_d, both of which were empirically developed using subtropical and summer temperate data sets, apparently compensate to some extent for effects due to their implicit dependence on pigment-specific absorption coefficients (a_ϕ^*). Clearly using incorrect specific absorption coefficients(subtropical) for both the B and K_d algorithm is better than using measured B(subarctic) with a subtropically "tuned" K_d algorithm (compare methods 1 & 2). Since a_ϕ^* varies temporally and spatially, a method independent of *B* was sought. By rearranging the CZCS algorithm and the primary production expressions, using a_ϕ instead of *B* as an input to the *P* expression, and relating the CZCS algorithm to a_ϕ instead of *B*, improved results for estimating *P* from remotely sensed data. Most importantly, there is no dependence on an accurate estimation of pigment-specific absorption coefficients (a_ϕ^*) for application of the absorption-based methods.

6. A paper titled "A method to derive ocean absorption coefficients from remote-sensing reflectance" by Lee at el. has been accepted for publication in Applied Optics.

A method to analytically derive in-water absorption coefficients from total remote-sensing reflectance (ratio of the upwelling radiance to downwelling irradiance above the surface) is presented. For measurements made in the Gulf of Mexico and Monterey Bay, with concentrations of [*chl a*] ranging from 0.07 to 50 mg/m^3, comparisons are made for the total absorption coefficients derived using the suggested method and those derived using diffuse attenuation coefficients. For these coastal to open ocean waters, including regions of upwelling and the Loop Current, the results are as follows: at 440 nm the difference between the two is 13.0% (r^2 = 0.96) for total absorption coefficients ranging from 0.02 to 2.0 m^{-1}; at 488 nm the difference is 14.5% (r^2 = 0.97); and at 550 nm the difference is 13.6% (r^2 = 0.96). The results indicate that the method presented works very well for retrieving in-water absorption coefficients exclusively from remotely measured signals, and that this method has a wide range of potential applications in oceanic remote sensing.

7. A newly revised version of chlorophyll a software has been delivered to MODIS oceans team to be merged into MODIS Beta delivery package.

8. A paper titled "SeaWiFS Algorithm for Chlorophyll *a* and Colored Dissolved Organic Matter in Subtropical Environments" by Kendall L. Carder, Steven K. Hawes, and Zhongping Lee has been submitted to Applied Optics for publishing.

Semi-analytical algorithms for phytoplankton and gelbstoff absorption and for chlorophyll *a* concentration are presented for use with the SeaWiFS sensor planned for launch on the SeaStar spacecraft in 1996. With slight modifications for spectral differences, the algorithms can be used with the Japanese Ocean Color and Temperature Scanner planned for launch by NASDA on the ADEOS satellite in 1996 and the Moderate Resolution Imaging Spectrometer planned for launch by NASA on EOS-1 in 1998. The approach is to separate absorption by gelbstoff and detritus from that by phytoplankton using the 412, 443, and 555 nm spectral bands. For waters with chlorophyll *a* concentrations of more than 5 mg m^{-3}, the algorithm switches to an empirical version relying on the 490-to-555 nm band ratio. In non-upwelling tropical and subtropical waters and summer temperate waters, the algorithm predicts phytoplankton absorption and chlorophyll *a* concentration with root-mean-square errors less than 32%. Waters tested are from the Arabian Sea, the North Pacific, the North Atlantic, and the Gulf of Mexico, with chlorophyll *a* concentrations ranging from 0.05 to 40 mg m^{-3}. The algorithm underestimates chlorophyll *a* concentration by about a factor of two for spring bloom and upwelling sites, and a similar error is expected for high-latitude waters. Accuracies for such sites can be improved using parameters for phytoplankton absorption consistent with the site and season.

The Coastal Zone Color Scanner (CZCS) was relatively successful in estimating chlorophyll-like pigment concentrations (C = chlorophyll *a* plus pheopigments) from space. This success was possible where C generally covaried with the optical properties of the water or for Case 1 waters [Morel and Prieur, 1977]. This covariance was necessary because the algorithm used only a single ratio of two spectral bands, which can only account for one variable. Furthermore, it has been shown that the global algorithm [Gordon et al., 1983], developed largely in summer temperate and subtropical waters, would generally underestimate high-latitude pigments [Mitchell and Holm-Hansen, 1991; Comiso et al., 1993; Arrigo et al., 1994] and could overestimate riverine pigments [Hochman et al., 1994]. Thus, the algorithm will perform better using parameters that vary with oceanographic region and perhaps with season.

One reason for this variation in optical properties is that the two components that affect water color the most, phytoplankton pigments and gelbstoff (also called colored dissolved organic matter or CDOM), do not always covary. For example, in Case 1 subtropical waters the absorption coefficient at 440 nm for CDOM, $a_g(440)$, usually ranges from about 0.3 to 0.7 times the absorption coefficient at 440 nm for phytoplankton, $a_\varphi(440)$ [Carder et al., 1989; Topliss et al., 1989; Walsh et al., 1992]. However, in some cases, such as after phytoplankton bloom senescence or in some coastal areas, this ratio has been estimated at about 2.0 to 3.6 [Walsh et al., 1992]. For areas where this ratio is high, two-band algorithms will overestimate both C and any primary production numbers that depend on C.

Carder et al. [1991] proposed that a satellite sensor with a short wavelength channel at around 410 nm could distinguish CDOM and other degradation products from chlorophyll. The basis for this idea is that CDOM and particulate detritus absorb more strongly at 410 nm than at 443 nm, whereas the opposite is true for phytoplankton. This short wavelength band can thus be used to discriminate between absorption due to CDOM and detritus and absorption due to phytoplankton. The Sea viewing Wide Field of view Sensor (SeaWiFS), to be launched by Orbital Sciences Corporation, will have spectral channels centered at 412, 443, 490, 510, 555, 670, 765, and 865 nm. Many other space-borne sensors, such as NASA's MODIS, NASDA's OCTS, and ESA's MERIS, all planned for launch on spacecraft later in the decade, will have spectral channels within a few nanometers of the visible SeaWiFS channels. Thus, algorithms based upon the visible SeaWiFS channels will enjoy broad applicability, providing a test bed for algorithms for the subsequent sensors.

Another reason for the regional and seasonal variation in optical properties of the ocean is that the absorption properties of the phytoplankton assemblage change. These changes can be attributed largely to the "package effect" and variation in pigment composition. Large, heavily pigmented cells absorb less light per unit chlorophyll *a* than do small lightly pigmented cells [Morel and Bricaud, 1981]. Also, cells growing under high light conditions require little chlorophyll *a* per cell to harvest light, and appear to require extra photo-protective pigments [Sosik and Mitchell, 1991; Morel et al., 1993]. Thus, some small cells grown in high light conditions result in very large chlorophyll-specific absorption coefficients (a() = a()/[chl *a*], *where [chl a] = chlorophyll a concentration).*

Since surface cells in oligotrophic subtropical environments tend to be smaller than either deep cells [Herbland et al., 1985] or coastal cells [Carder et al., 1986], where nutrients are more plentiful, they tend to have higher a() values [Carder et al., 1991]. However, this hypothesis that large cells dominate in waters with high nutrient and pigment concentrations must be carefully tested because grazing can rapidly reduce [chl a] without a commensurate change in a(). Thus, both the spectral shape of a() and the magnitude of the absorption *per unit of pigment can change with phytoplankton species composition and light and nutrient regimes, requiring different bio-optical algorithms for different environments.*

The backscattering due to particles can also change in magnitude and spectral shape as the concentration and size distribution of the particles vary [Gordon and Morel, 1983; Morel and Bricaud, 1986; Morel and Ahn, 1990; Kirk, 1994]. Here again, species composition, light–history, and nutrient availability are expected to influence backscattering, as well as is the relative abundance of living plants (i.e., phytoplankton) versus non-living particles (e.g., viruses, heterotrophic bacteria, and detritus). However, the effect of variation in backscattering on water color will be much less than the effect of variation in absorption.

An initial pigment algorithm for use with SeaWiFS data is presented here. The algorithm performs best in subtropical and summer temperate waters. With minor adjustments to the parameters for phytoplankton absorption, it can be applied to other environments, but this paper will only cover the basic subtropical algorithm. Since the algorithm does not necessarily account for the effects of suspended sediments, coccolithophore blooms, or bottom reflection, all of which may have varying albedos, use of the term "Case 2 algorithm" would be misleading. Since the algorithm presented does account for the absorption effects of phytoplankton and CDOM separately, it will be referred to as the "chl-and-CDOM algorithm."

The algorithm is based on a semi-analytical model of remote sensing reflectance (Rrs). It is an extension of the irradiance *reflectance algorithm for [chl a] discussed in Carder et al. [1991]. The major differences between the earlier algorithm and the present one occur in the particle backscattering and phytoplankton absorption terms. Given input Rrs() values, the algorithm first estimates the absorption coefficient of phytoplankton at 675 nm, a(675), by means of the absorption due to phytoplankton at blue wavelengths. The absorption coefficient of CDOM at 400 nm, ag(400) is calculated at the same time. [chl a] is then calculated from the a(675) value. Furthermore, a() for all of the SeaWiFS wavebands can be calculated from a(675) based on empirical relationships.*

Optical and bio-optical data from several different cruises are used to

develop the algorithm parameters. These data usually include hyperspectral measurements of Rrs [Carder and Steward, 1985; Lee et al., 1994; Lee, 1994], the absorption coefficient for particles, detritus, and CDOM (ap, ad, and ag, respectively), and chlorophyll a and pheopigment concentrations.

Hyperspectral Rrs() was measured above the water from a ship by the method developed by Carder and Steward [1985] with a Spectron Engineering spectral radiometer (model SE-590). The water-leaving radiance and downwelling sky radiance were measured directly with the SE-590 and total downwelling irradiance was measured by viewing a standard diffuse reflector (Spectralon, 10%). Reflected sky radiance from the sea surface was corrected for by the method of Carder and Steward [1985] when calculating Rrs(). Fresnel reflectance for skylight was calculated based on the angle of reflection.

Measurements of ap() and ad() were obtained in the following manner. The method described by Mitchell and Kiefer [1988] was used with a Lambertian diffuser added between the light source and the filter pad to minimize any dependence of the diffuse transmittance on the optical geometry of the light which is incident on the pad. The SE-590 radiometer, which has a 10^0 acceptance angle, was used to measure the transmitted light. Water samples ranging from 300 ml to several liters were filtered through Whatman GF/F filter pads, and the transmission spectra (380–780 nm) of these pads were measured and divided by the transmission spectrum of a wetted blank GF/F pad to obtain the optical density (OD()) of the particles. After this measurement each sample was soaked in hot methanol [Kishino et al., 1985; Roesler et al., 1989] for about 15 minutes to remove pigments, rinsed with deionized water, and its transmission spectra was again measured. This measured spectrum was divided by the transmission spectrum of a blank GF/F pad that was flushed with methanol and rinsed with deionized water to obtain the OD of the resulting "detrital" component. ODs were corrected for large particle scattering by setting the OD(780) equal to zero. ap() and ad() were calculated from the corrected optical densities using the "ß factor" formulation of Bricaud and Stramski [1990] to correct for optical pathlength elongation due to scattering within the pad. Only samples where OD(675) exceeded 0.04 were used in order to minimize spurious ß effects at low OD. The difference between ap() and ad() provides a().

ag() was measured as follows. For the MLML 2 cruise, water samples were filtered through 0.2 µm pore diameter Nuclepore *membrane filters. The absorption coefficient of the resulting filtrate was measured on a Cary 2000 spectrophotometer with a 10 cm pathlength cell. For the GOMEX and COLOR cruises, water samples were filtered through Whatman GF/F (pore diameter*

0.7 μm) and Gelman Supor 200 (pore diameter 0.2 μm) filters. The absorption coefficient of the resulting filtrate was measured with a spectrophotometer with a 1 meter pathlength [Peacock et al., 1994]. ag measurements for the other cruises are either unavailable or they are not needed for this study. Chlorophyll a and pheopigment concentrations were measured using the method of Holm-Hansen and Riemann [1978].